Development of a New Long Duration Solar Powered Autonomous Surface Vehicle

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***Abstract*-This paper introduces recent activities associated with the development of a new long duration solar powered autonomous surface vehicle (ASV) known as the Ocean Atmosphere Sensor Integration System (OASIS). A brief discussion of ASV applications, platform research and development, and challenges is presented. Platform development objectives and the relationship to resulting systems, hull and deck design, and deployment and recovery are highlighted. The paper discusses the development approach, technology, and architecture for the onboard and off-board control systems. A brief chronology of the hardware integration and on water checkout is also provided. A synopsis of current and future collision avoidance considerations is presented.**

I. INTRODUCTION

Autonomous and Lagrangian platforms and sensors (ALPS) are an important tool for collecting in situ ocean and atmospheric measurements which complement the wealth of data available from NASA/NOAA space based ocean observations including sea surface temperature (SST), surface winds, salinity, colored dissolved organic matter (CDOM), and large scale circulation patterns. ALPS exist in a number of form factors including surface drifters, floats, gliders, autonomous underwater vehicles (AUV), and autonomous surface vehicles (ASV). Recent advances in technology as well as a push to develop a global ocean observing system have resulted in a diverse collection of ALPS with varying modes of operation, mission durations, ranges, and payload carrying capacities [1].

This paper introduces recent activities in the development of a new long duration solar powered ASV known as the Ocean Atmosphere Sensor Integration System (OASIS). The OASIS ASV is being developed to provide a low-cost, low-speed, navigable, reusable, re-configurable, long-duration, open ocean observing platform. The vision is to develop and deploy a fleet of ASV platforms hosting a diverse set of sensors to obtain biogeochemical and air-sea process measurements in a manner that reduces overall sampling mission costs. Section II provides a synopsis of ASV applications, platform research and development, and challenges. Section III highlights

Figure 1. The Ocean Atmosphere Sensor Integration System (OASIS) ASV.

OASIS platform development objectives and the relationship to resulting systems, hull and deck design, and vehicle deployment and recovery. Section IV discusses the development approach, hardware and software technology, and architecture associated with onboard and off-board control systems. A brief chronology of the hardware integration and on water checkout activities area discussed. Section VI presents a synopsis of current and future collision avoidance considerations.

Fabrication of the OASIS 1 platform has been completed and land and water based shakedown activities have been underway since the beginning of the development life cycle. The first platform is considered an R&D version and will no doubt continue to undergo modification and enhancement. Fabrication of the second R&D platform, OASIS 2, is also underway. Both platforms will begin supporting science applications in parallel with ongoing engineering activities.

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the nearby Delaware, Maryland, Virginia (DELMARVA) costal region and also includes the deployment of a high frequency costal radar system, costal bio-optical buoys, and ship-based sampling cruises.

II. Motivation & Background

This section highlights ASV applications, research and development, and challenges to set the context for the development of a new long duration ASV.

A. *Potential Applications*

ASV platforms applied to research, civil, and military operations offers the potential for reducing operational costs, increasing the quantity, frequency, and spatial coverage of measurements, and reducing the exposure of humans to hazardous and hostile environments. Oceanographic, atmospheric, and environmental research can benefit from the application of ASV platforms by supporting the collection of in situ measurements at the ocean-atmosphere boundary layer. Measurements include, but are not limited to, surface winds, air temperature, humidity, sea surface temperature, salinity, ocean color, currents, and chemistry. Platforms may function as mobile buoys and Lagrangian drifters. They may also support calibration and validation of remotely sensed measurements from air and space. ASV platform may also support mapping of dynamic features such as Harmful Algal Blooms (HAB) and oil spills. Vertical profiling and sample return support are also possible. Operational civil applications include weather forecasting, hurricane path prediction, and search and rescue. Military and law enforcement operations for homeland security, port/harbor surveillance, mine detection, and reconnaissance may also benefit from using ASV platforms.

B. *Research & Development*

ASV platforms vary in speed, endurance, range, power, payload capacity, hull geometry, and level of autonomy. Short duration ASV platforms are under development in academia, government, and industry. Recent ASV research and development in academia includes the work of the AUV Laboratory at MIT for the development of the AutoCat Autonomous Surface Craft which is being used for bathymetric mapping and experiments in networked vehicle operations [2]. The MIT Department of Ocean Engineering has also developed the Surface Craft for Undersea and Oceanographic Testing (SCOUT) for use as a low-cost testbed for AUV algorithm development [3]. Commercial platforms from Sea Robotics Corporation such as the USV-1000 provide small low cost solutions for the deployment of short term sampling surveys [4]. Industry is developing short duration, high speed surface platforms for military applications. This class of platforms can host cameras, radars, and environmental sensors for real time surveillance. DRS Training & Control Systems, Inc. has developed a vehicle known as Sea OWL [5] and Accurate Automation Corporation has developed and delivered vehicles to the Office of Naval Research and Naval Sea Systems Command [6].

The Falmouth Scientific, Inc. SAUV II is a solar powered long duration vehicle that enables long term oceanographic monitoring and profiling [7]. SAUV II is a hybrid vehicle exhibiting characteristics of an ASV, AUV, and glider.

C. *Challenges*

ASV platforms face a wide range of operational challenges at sea. Collision with mobile marine surface assets is a growing concern in the community and will gain additional attention as new platforms are developed and deployed. Platforms operating autonomously in large lakes, bays, and open ocean conditions for extended periods of time should be designed to be self righting. Hull design should also minimize drag and maximize payload capacity. Long duration remote surface operations for scientific applications suggest a “live off the land” approach in which platforms collect, store, and hardness solar, wind, and wave energy. Varying environmental conditions and operational latitudes will ultimately drive the level of solar energy that can be acquired. Platform geometry, weight, navigation, speed, and endurance are all drivers for determining ease of deployment and recovery. Ideally, an ASV can be deployed and recovered shore side to minimize ship costs. Acceptable costs for ASV platforms focused on scientific and operational observational missions will be market driven and dependent on capability and alternative modes of in situ data collection. Biofouling, while not unique to ASV platforms, is a driver for determining mission duration before requiring servicing.

III. New Platform Development

This section highlights OASIS platform development objectives and implications. It also discusses platform deck/hull arrangement and deployment/recovery approaches.

A. *Development Objectives*

The OASIS platform is being developed to function as a low-cost, long-duration, reusable, navigable, open ocean platform focusing on the collection of measurements at the ocean–atmosphere boundary layer. Intended applications may include observations off conventional shipping routes, routine transects, dynamic feature mapping, support for weather forecasting, and hurricane research. Table I summarizes the key OASIS platform development objectives.

TABLE I
Platform Development Objectives and Implications

Aspect	Objective	Implication
Applications	Air – Sea Measurements	Surface vehicle
Communication	Real-time, two-way, local & global	RF and satellite
Cost	Low, less than typical COTS AUV	Off the shelf components, easy to produce
Deployment, Recovery, Transport	Shore deployments from standard boat ramp	Boat trailer for transport
Endurance	Long Duration (~3-6 months or greater per	Regenerative power (solar, wind)

	deployment)	
Navigation	Autonomous, course tracking, station keeping	GPS, compass, autopilot
Payload	+500lbs, varies by platform, above surface measurements	Flexible payload bay, mast
Power	Regenerative (solar, wind)	Area to support solar panel mounting
Speed	Low (~2.2 – 2.5 knots average cruise)	Reduces power consumption
Region	Open Ocean	Self-Righting, rugged

B. *Systems Overview*

The platform is comprised of five core systems. The structures system consists of a custom fiberglass hull/deck, internal aluminum stiffeners, and a mast. The power subsystem is composed of six solar panels, a charge controller, twelve 12 volt deep cycle lead-acid marine batteries, DC-DC converters, and a power bus. The system also includes a ventilation fan to evacuate hydrogen gas from the platform interior during charging. The propulsion system includes rudder and propeller control surfaces. A stepper motor actuates the rudder and a servo motor directly drives the propeller. The safety system includes navigation lights, radar reflectors, and an automatic bilge pump. The onboard control system includes a single board computer, communications hardware, navigation sensors, motor drivers, and control software.

C. *Hull and Deck Arrangement*

Donald L. Blount and Associates, Inc. (DLBA) provided the naval architecting expertise required to design the platform hull and deck parts. DLBA Robotics, Ltd. then produced the limited production molds and fabricated the fiberglass deck and hull parts for the first two platforms. The resulting platform geometry is largely the function of the requirements to be self-righting and to accommodate COTS solar panels. The hull skin is self supporting while the flat areas on the deck require additional aluminum stiffener in the form of square tubing. During operational deployments the two parts will be mated using a marine sealant. The halves are currently bolted together and sealed with a foam gasket to allow easy separation during the development phase of the project. There are three water tight compartments separated by two bulk heads. The forward section serves as the primary payload bay and will includes water sampling support as well as a downward looking portal for sensor mounting. The middle section contains the battery compartment located at the base of the keel. It also contains the bulk of the components comprising the onboard control system and may also be used for payload. The aft compartment contains the propulsion and rudder control hardware. In the future, a vertical profiling system may be installed in this area forward of the propulsion motor. A single servicing hatch is located to provide access to the central compartment. Internal hatches provide access to the forward and aft compartments.

TABLE II
PLATFORM CHARACTERISTICS

Characteristic	Value
Dimensions	Length = ~18FT Width = ~5FT Height = ~6FT (keel to “dog house” peak)
Draft	26 in
Mast	~10FT
Weight	~3000lbs

Figure 2. Port side view of OASIS ASV on trailer.

D. *Deployment and Recovery*

The platform is easily transported, deployed, and recovered on a single boat trailer at most boat ramps. Deployment on ramps with subtle grades is achievable through the use of a trailer tongue extension to help achieve the additional water depths necessary to float the vehicle off the trailer. The mast on the OASIS 1 is hinged to more easily support transport, raising prior to operations, and lowering after recovery. Once in the water, the platform is quite nimble and can be manually piloted shore side to larger waters. When there is not a clear line of sight between the deployment ramp and shore side mobile operation vantage point, the platform can be escorted under tow or manual remote control using a small support boat.

IV. PLATFORM CONTROL SYSTEMS DEVELOPMENT

Emergent Space Technologies, Inc. (Emergent) developed the core onboard control system which encompasses the software and hardware that enable all major platform functions including support for vehicle commanding, telemetry generation, guidance navigation and control (GN&C), subsystem hardware management and interfacing, state handling, diagnostics, and health and safety. Emergent has also developed the off board support infrastructure that manages communication hardware and provides a graphical user interface (GUI) for vehicle commanding and monitoring.

A. *Development Approach*

In order to maximize the results of a lean development budget, a spiral development process was adopted to incrementally build up and demonstrate system capability. The use of commercial off the shelf (COTS) hardware, open source

software libraries, frameworks, tools, and applications have also greatly reduced overall system development costs.

B. *Operations Concept*

The onboard control system currently supports two main modes of control. The first enables direct manual control of the vehicle propulsion and steering system for deployment, recovery, testing, and system override via laptop or handheld control device. The second supports autonomous guidance navigation and control (GN&C) for course tracking and station keeping. Commands transmitted to the vehicle configure system parameters, upload courses, and engage autopilot operation. The vehicle may be monitored during course tracking and station keeping, or operate unattended. Upon completion of an assigned course, the vehicle will station keep at the final course waypoint until additional instructions are received. In the future, a third mode of operation is planned to provide for onboard intelligent autonomous control via installation of custom behavioral algorithms on the onboard main computer or an alternate networked controller which may be part of a specialized payload. Such capability may further enable applications including dynamic feature tracking, collaboration with other platforms, and sensor web behaviors.

C. *Hardware Technology*

A standard suite of COTS onboard navigation sensors have been integrated onboard and include a GPS receiver, digital compass, roll/pitch inclinometers, and 3-axis inertial sensor. A 2-axis motion controller provides signals to drive the propulsion servo motor and rudder stepper motor. The propulsion motor speed and direction are controllable. The rudder stepper motor is attached to a ball screw that actuates a tiller arm attached to the rudder shaft to provide rudder deflection. Rudder closed loop support is achieved through the addition of an absolute optical encoder on the rudder shaft. Communications are supported through 900 MHz Freewave spread-spectrum radios. An Iridium satellite modem supports global operations and currently serves as a backup to radio communications during testing. The Iridium antenna is mounted to the platform "dog house" rather than on the mast, to ensure that the loss of the mast does not terminate a mission. The onboard main controller (OMC) is a rugged embedded single board computer. The onboard communications bus connects all hardware through the use of an Ethernet local area network (LAN). All supporting hardware provides an Ethernet or serial interface. Serial devices connect directly to the OMC or a serial to Ethernet adapter. Core meteorological measurements including wind speed and direction, barometric pressure, humidity, and temperature measurements are obtained from mast mounted sensors. Mission specific payload sensors and hardware may be installed onboard and operate either as standalone or loosely coupled components.

D. *Software Technology*

The OMC runs a Linux Operating System (OS). The on and off board control system software is implemented in Java and requires the Standard Edition (J2SE) Java runtime environment (JRE). Third-party open source technologies and standards have been used where possible to reduce development and maintenance costs. The control system software makes use of the NASA Goddard Space Flight Center (GSFC) developed Instrument Remote Control (IRC) framework. The generic IRC framework simplified the development of the overall control system by providing a flexible and extensible foundation on which to develop on and off board systems.

E. *Onboard Architecture*

The core onboard control system software architecture was designed to be highly modular, re-configurable, and extensible to support near term system development, future customization, and flexibility for use on alternate surface platforms. The IRC framework contributed to the modular architecture by facilitating a software design pattern consisting of device proxies, input/output adapters, connections, messages, and state models to interface with each hardware component in a standard way. Connection classes facilitate communication with hardware by providing common support for serial, TCP/IP, UDP and other communication interfaces. Input adapters attach to data streams from connections and provide the ability to parse data from the hardware into messages. Output adapters operate conversely by processing messages to format commands that are streamed to a connection for transmission to hardware. Device proxies exchange message with adapters and the rest of the system. State models help proxies track hardware state. Extensible Markup Language (XML) technology is an integral component of IRC and helps facilitate system reconfiguration without software recompilation. XML descriptions are used extensively onboard to define devices and associated adapters, connections, and configuration parameters for each hardware component. The ability to maintain different system configurations for development, bench testing, and onboard environments is extremely useful. Extensibility is supported through the use of Java and an object oriented architecture that provides default implementations and standard interfaces for key system components.

The core onboard control system is composed of seven major subsystems—propulsion, communications, command and data handling (C&DH), guidance navigation & control (GN&C), attitude determination, power, and core meteorological sensors. The propulsion subsystem supports rudder angle deflection and propulsion motor speed and direction control through the use of a dual axis motion controller that drives the rudder stepper motor and propulsion servo motor. This subsystem also monitors actual rudder position, propulsion shaft revolutions per minute (RPM), and servo current draw. The communications subsystem manages onboard communications hardware including Freewave radios and Iridium satellite modems and handles the low level packet protocol used for communication of commands and telemetry. The C&DH subsystem provides support for onboard command validation and processing, real time and playback telemetry generation, onboard communication bus, data archiving, state

distribution, and event logging. The subsystem also provides a watchdog capability, which can be configured to safe the vehicle or re-initialize the control system upon detection of predefined events. The GN&C subsystem interfaces with navigation sensors including a GPS receiver and digital compass to obtain time, position, velocity, and heading measurements. The subsystem enables direct manual control or autonomous control through the use of a custom autopilot implementation. The autopilot provides support for course and mode management, station keeping, course tracking, diagnostics, and control law interfacing. The attitude determination subsystems interfaces with roll/pitch inclinometers and a 6 degree of freedom (DOF) inertial sensor to provide vehicle rates and linear accelerations. The power subsystem provides support for main bus voltage monitoring and circuit control. An off the shelf charge controller autonomously manages solar panels for efficient battery charging, greatly simplifying the overall power subsystem. Finally a basic set of meteorological sensors is integrated as core sensors to provide for measurements such as wind speed and direction, humidity, barometric pressure, and temperature.

In the months ahead, we will begin development and integration of an onboard application and autonomy layer. The architecture utilizes robust message oriented middleware (MOM) technology to enable loosely coupled re-configurable components to support mission specific payload integration as well as installation of behavioral algorithms to enable capabilities such as event/response, sensor networks, dynamic mapping, and collaboration.

F. Off-board Architecture

Off board systems are built using the same technologies and architectures as described for the onboard system. The current off board systems provides a Graphical User Interface (GUI) for vehicle commanding and telemetry monitoring during integration, testing, and operational activities. Command definitions are supported using XML and are graphically rendered by the system to simplify development. Real time data is monitored using strip charts and tabular displays. Off board systems also support communications hardware interfaces.

V. Integration and Checkout Activities

This section provides a brief chronology of integration and checkout activities associated with the development of the first OASIS platform. Onboard systems planning and design began during the second quarter of 2004 and software development for onboard and off-board infrastructure got underway during the third quarter. December 2004 marked the arrival of the first substantial set of core onboard components required for the propulsion subsystem and kicked off hardware integration and bench testing activities.

During the first quarter of 2005 the initial version of the onboard main controller, spread spectrum radios, and propulsion and rudder hardware were installed onboard the platform. In March the first on water shakedown activity was

Figure 3. OASIS checkout in Chincoteague Bay.

Figure 4. View from support boat.

conducted on the Chincoteague Bay to checkout propulsion and communication systems under manual remote control. The second and third quarters focused on hardware integration and bench testing to support navigation and wind monitoring hardware as well as checkout of two alternate propulsion systems. At the conclusion of July's on water shakedown activity a stable system had been demonstrated under manual control with vehicle telemetry monitoring from a shore side laptop control station. Additional hardware was integrated during the fourth quarter to provide for longer range radio communications and propulsion shaft RPM measurements. The main focus however, was on preliminary development and checkout of the onboard autonomous GN&C support. November and December 2005 water activities demonstrated the platforms initial ability to track courses of one to three closely spaced (<0.5km) waypoints.

The remainder of the core onboard hardware was integrated during the first half of 2006 and included support for vehicle dynamics monitoring (roll/pitch, rates, and accelerations), rudder position detection, and Iridium satellite communications. Water activities have emphasized increasing the duration and

test course size to checkout autonomous GN&C updates as well as overall core system robustness. The May 2006 on water activity was conducted on the Pocomoke Sound on the Chesapeake Bay to provide for a more expansive test site. Two test courses of approximately four and six nautical miles were used for vehicle testing. Waypoints were space approximately one nautical mile apart. Visual monitoring was conducted from an on water support boat as well as from shore while monitoring vehicle telemetry in real time via laptop control station. During the months ahead we will being payload integration and migrate to longer duration station keeping and transect tests in the Chesapeake Bay and off the DELMARVA coast to further checkout the vehicle.

VI. Collision Avoidance Considerations

The International Regulations for Prevention of Collisions at Sea, 1972 (72 COLREGS), defines the international navigation rules that "apply to all vessels upon the high seas and in all waters connected therewith navigable by seagoing vessels" [7]. The OASIS ASV currently displays mast mounted day shapes and lights as prescribed by the COLREGS Rule 27, to alert vessels in visual proximity, that the ASV is Not Under Command (NUC) or restricted in its ability to maneuver. Day shapes are implemented on OASIS through the display of two black spherical radar reflectors in vertical line. Two groups of all around red lights in vertical line are also displayed. Vessels encountering another vessel displaying the NUC designation have the responsibility to "give way" to avoid collision. The COLREGS rules were developed for use by vessels with human operators onboard. The rules address vessel responsibilities and conduct in the proximity of other vessels. They also define the display of lights and shapes, and the use of sounds and light signals. A detailed discussion on legal issues associated with the operation of autonomous marine vehicles and approaches for implementation of COLREGS rules onboard is covered in [8].

The emergence of low cost hardware to support the shipboard Automatic Identification System (AIS) may aid an ASV in implementation of some of the COLREGS rules. Vessels carrying AIS transponders broadcast state messages over VHF to vessels and the Vessel Traffic Services (VTS) in proximity that are equipped with an AIS receiver. Messages provide information about a vessel including its name, size, type, speed over ground (SOG), and course over ground (COG). ASV platforms equipped with AIS receivers could acquire this information and react as necessary to avoid collision. ASV platforms with AIS transponders could alert vessels to the ASV presence and current state.

VII. Conclusion

The OASIS platform team has made significant accomplishments in development, integration, and test of the first of a planned fleet of long duration ASV platforms. A second ASV is now under development and expected to begin in water activities by early Fall 2006. Near term activities will focus on platform checkout under longer durations and in higher sea state conditions. In parallel we will begin payload integration to support oceanographic applications.

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